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Fundamentals of Electric Motor Drives

Electric machines are an essential part of industry. They provide the necessary mechanical-to-electrical or electrical-to-mechanical conversion. In the United States, more than 50% of the electric power is consumed by electric motors. The motors perform many different functions, from small applications like cooling fans in your personal computer that consume only a few watts of power all the way to huge pumps that consume megawatts.

The majority of motors used today, approximately 80%, are three-phase induction motors. Motors themselves have limited capabilities. In more complicated and technical applications, the motor itself does not perform the necessary tasks. Today, a complete electric drive system is needed to control and manipulate the motor to fit specific applications. An electric drive system involves the control of electric motors in steady-state and dynamic operations. The system should take into account the type of mechanical load.

There are many different types of mechanical loads. When defining a load, torque versus speed characteristics are explored. The

relationship is then used to design the type of electric drive system. In the past, electric drive systems required large and expensive equipment. These systems were inefficient and limited to the specific applications they were designed for.

Today, with advancements in power electronics, control electronics, microprocessors, microcontrollers, and digital signal processors (DSPs), electric drive systems have improved drastically. Power electronic drives are more reliable, more efficient, and less expensive. In fact, a power electronic drive on average consumes 25% less energy than a classic motor drive system. The advancements in solid-state technologies are making it possible to build the necessary power electronic converters for electric drive systems.

The power electronic devices allow motors to be used in more precise applications. Such systems may include highly precise speed or position control. Systems that used to be controlled pneumatically and hydrolically can now be controlled electrically as well.

3.1 POWER ELECTRONIC DEVICES

The *power diode* is the simplest, uncontrollable power electronic switch. A power diode is forward biased (on) when its current is positive and reverse biased (off) when its voltage is negative.

A *thyristor* is a controllable three-terminal device. If a current pulse is applied to its gate, the thyristor can be turned on and conducts current from its anode to cathode, providing a positive anode-to-cathode voltage. However, in order to turn a thyristor on, the gate current must be above a minimum value I_{GT} . After the thyristor turns on, if its current (i.e., anode to cathode) reaches above a minimum value called latching current I_L , the gate current is no longer required. The thyristor will continue to conduct until its current falls below a minimum value called holding current I_H .

A *diac* is a two-terminal power electronic device. When the voltage across the terminals reaches the diac specific voltage, the diac is turned on and conducts current from the positive terminal to the negative terminal. The voltage across terminals decreases to a small value which is the voltage drop while diac is on. A diac is a bidirectional device.

A *triac* is a three-terminal, controllable power electronic switch. The operation of a triac is equivalent to two thyristors which are parallel in opposite directions. Therefore, a triac has the capability of conducting current in both directions. Gate current can also be positive or negative. As a result, a triac has four different operating modes.

Power transistors have the characteristics of conventional transistors. However, they have the capability of conducting higher collector current. They have also higher breakdown voltage V_{CEO} . Power transistors are designed for high-current, high-voltage, and high-power applications. They are usually operated either in the fully on or fully off state.

Power MOSFETs are voltage-controlled devices. They are usually N-channel and of the enhancement type. Most power MOSFETs are off when $V_{GS} < 2$ V and are on when $V_{GS} > 4$ V. When a power MOSFET is on there is a small resistance, i.e., less than $1\ \Omega$, between drain and source, and when it is off there is a large resistance (almost open circuit) between drain and source.

Isolated gate bipolar transistors (IGBTs) are equivalent to power transistors whose bases are driven by MOSFETs. Similar to a MOSFET, an IGBT has a high impedance gate, which requires only a small amount of energy to switch the device. Like a power transistor, an IGBT has a small on-state voltage.

Unijunction transistors (UJT) are three-terminal devices with one emitter and two bases. It can be assumed that between the two bases two resistors are connected in series. If in the forward-biased mode the emitter voltage reaches the voltage divided between the two resistors, emitter current suddenly increases and the device conducts.

Pulse transformers are similar to conventional transformers. However, they are designed for high-frequency and very low-power applications. They are not for transforming power from the primary to the secondary. They are used for isolating control circuits from power circuits in power electronic applications.

3.2 ELECTRIC MOTOR DRIVES

An electric motor drive system is made up of five main components. Figure 3.1 shows a block diagram of an electric motor drive. The input to the drive is the power source. The power source is the energy for the system. Next is the power electronic converter. The electronic converter manipulates the voltage, current, and frequency provided by the power source. To control the system, a controller is needed. Of course, the remaining two components of the system are a motor and a mechanical load.

In the following sections, different types of electric motor drive systems are explored. Drives for DC and AC motors are explained in detail.

3.3 SINGLE-PHASE, HALF-WAVE, CONTROLLED RECTIFIER

Shown in Fig. 3.2 is a separately excited DC motor controlled by a single-phase, half-wave controlled rectifier. This rectifier provides speed control for the separately excited DC motor by varying armature voltage and current.

The steady state voltage and torque equations for a separately excited DC motor are

$$V_a = R_a I_a + E_a$$

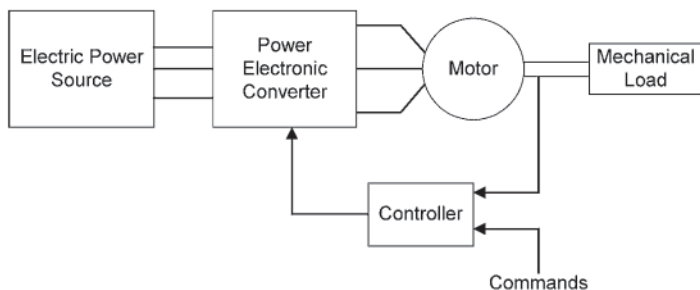


FIGURE 3.1 Block diagram of an electric motor drive.

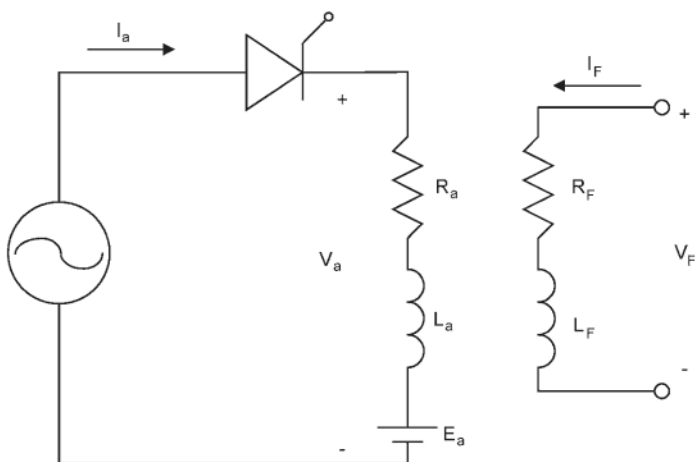


FIGURE 3.2 Single-phase, half-wave, controlled rectifier.

$$V_F = R_F I_F$$

$$E_a = K I_F \omega$$

$$T = K I_F I_a$$

Combining these equations, we get

$$\omega = \frac{V_a - R_a I_a}{K I_F}$$

or

$$\omega = \frac{V_a}{K I_F} - \frac{R_a T}{(K I_F)^2}$$

As seen from these equations, speed control can be done by varying R_a , V_a , and I_F . Varying R_a can only increase the speed. Also, by varying R_a , we increase the losses $I^2 R$. I_F can only be decreased. This is accomplished by putting resistance in the field. Again, this increases

the I^2R losses. Control of V_f is limited because of saturation. The best method of controlling the speed of the motor is to control V_a . Using a thyristor, as shown in Fig. 3.2, the average of V_a can be controlled. Figure 3.3 shows the voltage and current for a separately excited DC motor controlled by a single-phase, half-wave, controlled rectifier. As seen in Fig. 3.3, α represents the firing angle of the thyristor. This is where the thyristor turns on. Also seen in Fig. 3.3 is β . β is where the current I_a reaches zero and the thyristor turns off. From these two quantities, we define the conduction angle:

$$\gamma = \beta - \alpha$$

By changing the conduction angle, the average value of V_a is varied. When V_a is varied, the speed of the motor is changed. This is a simple but effective speed controller.

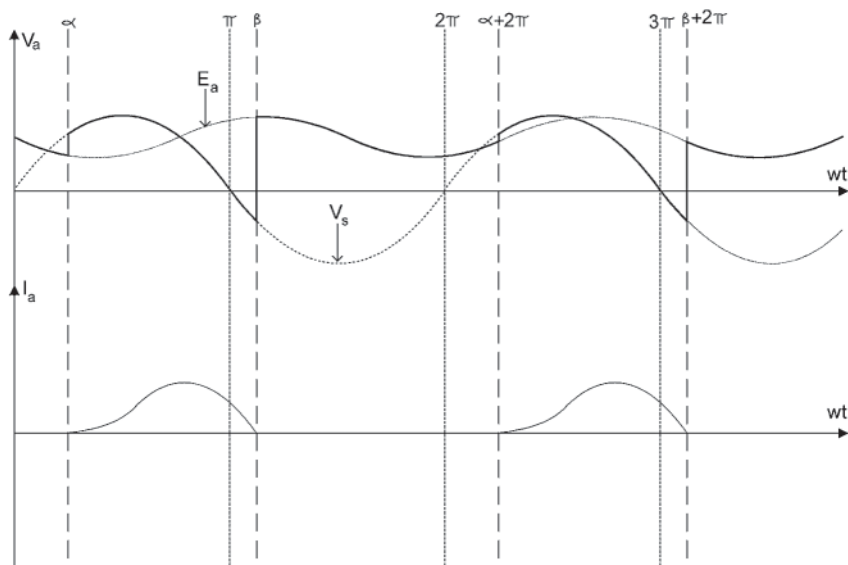


FIGURE 3.3 Voltage and current for Fig. 3.2.

3.4 SINGLE-PHASE, FULL-WAVE, CONTROLLED RECTIFIER

The next electric drive discussed is a single-phase, full-wave controlled rectifier. This adjustable speed drive is similar to the single-phase, half-wave controlled rectifier. As an example, this rectifier is presented to control a separately excited DC motor. The single-phase, full-wave controlled rectifier consists of four thyristors. The increase in thyristors provides for better control compared to the half-wave controlled rectifier. The obvious disadvantage of the full-wave rectifier is the increase in price because of the increase in the number of thyristor. Figure 3.4 shows a separately excited DC motor controlled by a single-phase, full-wave controlled rectifier.

There are three different modes of operation for the single-phase, full-wave controlled rectifier. The first is discontinuous conduction mode (DCM). In DCM, the current I_a reaches zero and stays at zero for a certain period of time. The next mode is continuous conduction mode (CCM). In CCM, I_a does not reach zero at any point during the period. The final mode of operation is critically discontinuous

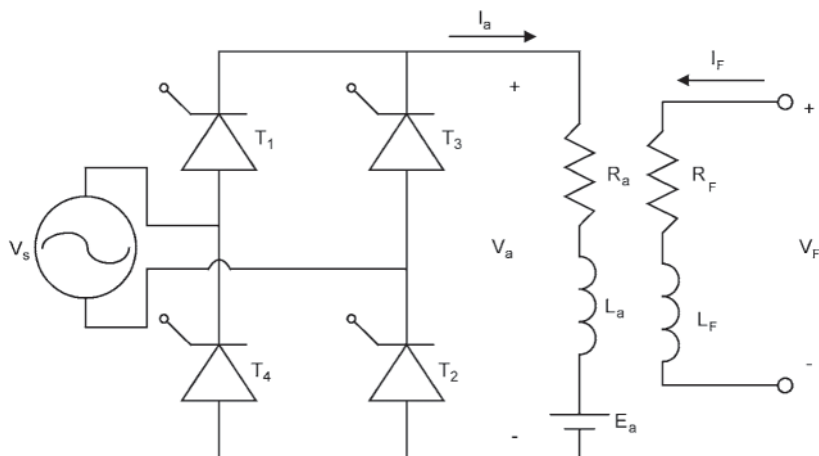


FIGURE 3.4 Single-phase, full-wave, controlled rectifier.

conduction mode (CDCM). In CDCM, the current I_a reaches zero and then immediately starts to increase.

Unlike the half-wave rectifier, the full-wave rectifier has the ability to manipulate the current when V_s is negative. There are three modes in DCM. The first mode is when from time $t = 0$ until α . Mode one is shown in Fig. 3.5. In mode one, there is no current in the armature; this results in a V_a equal to the back emf E_a .

Mode two occurs when the source voltage V_s is positive. Mode two is shown in Fig. 3.6. In mode two, T_1 and T_2 are conducting and T_3 and T_4 are not conducting. V_a is equal to the source voltage V_s .

The final mode is mode three. Mode three is shown in Fig. 3.7. This mode is the opposite of mode two. In mode three, T_3 and T_4 are conducting and T_1 and T_2 are not conducting. This makes the voltage V_a equal to the negative of the source voltage V_s .

Figure 3.8 shows the waveforms of the rectifier in DCM. As seen in Fig. 3.8, the conducting angle occurs twice per period, once when the source voltage V_s is positive and again when the source

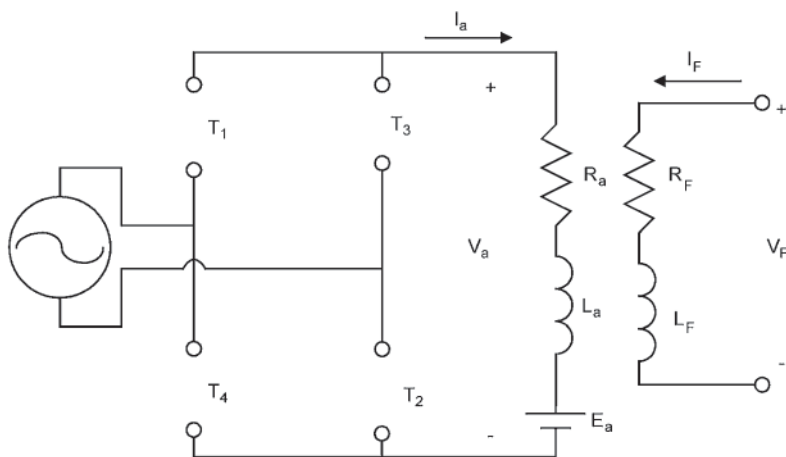


FIGURE 3.5 Mode one of DCM.

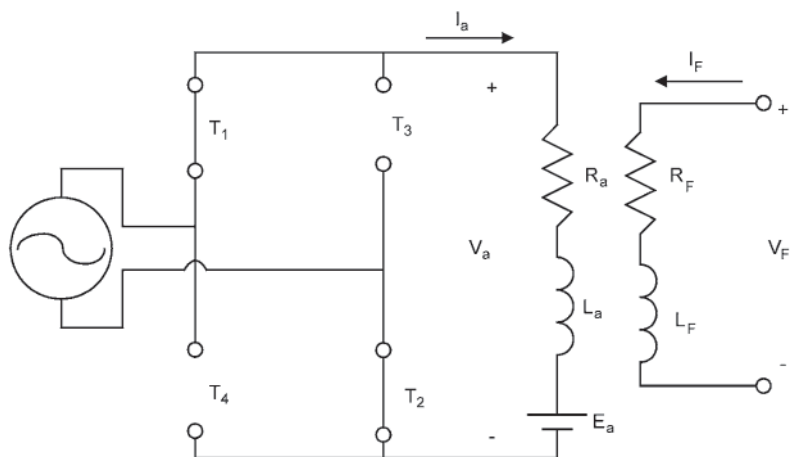


FIGURE 3.6 Mode two of DCM.

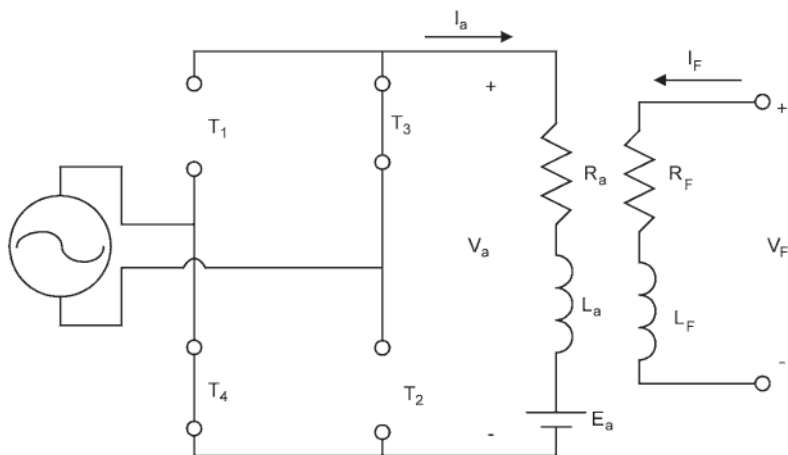


FIGURE 3.7 Mode three of DCM.

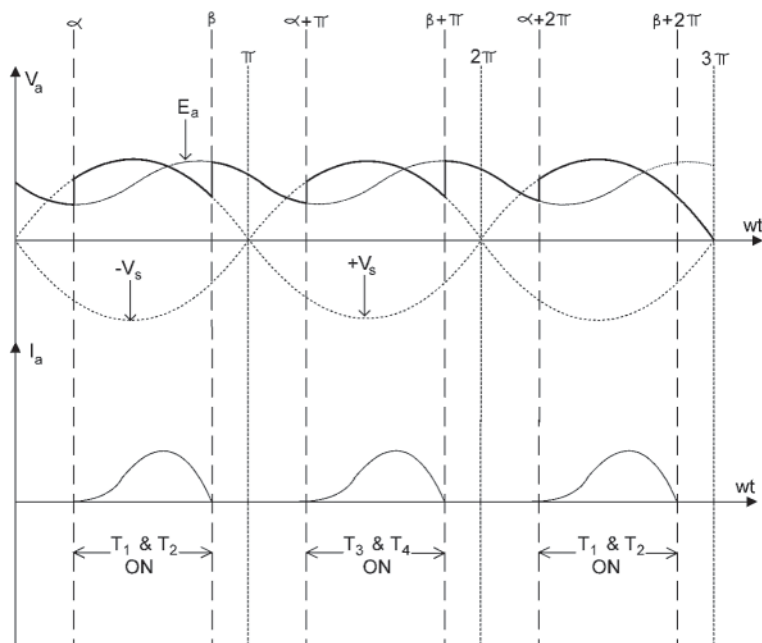


FIGURE 3.8 Waveforms of a single-phase, full-wave controlled rectifier in DCM.

voltage is negative. In addition, in mode one, the voltage V_a is equal to the back EMF E_a until α .

Continuous conduction mode is similar to DCM, but in CCM mode one does not exist. Figure 3.9 shows the circuit operating in CCM. CCM occurs when V_a is large compared to E_a . Notice that V_a is never equal to E_a .

3.5 PHASE-CONTROLLED INDUCTION MOTOR DRIVES

As mentioned earlier, three-phase induction motors make up the majority of the motors in the industry. This is because of their low

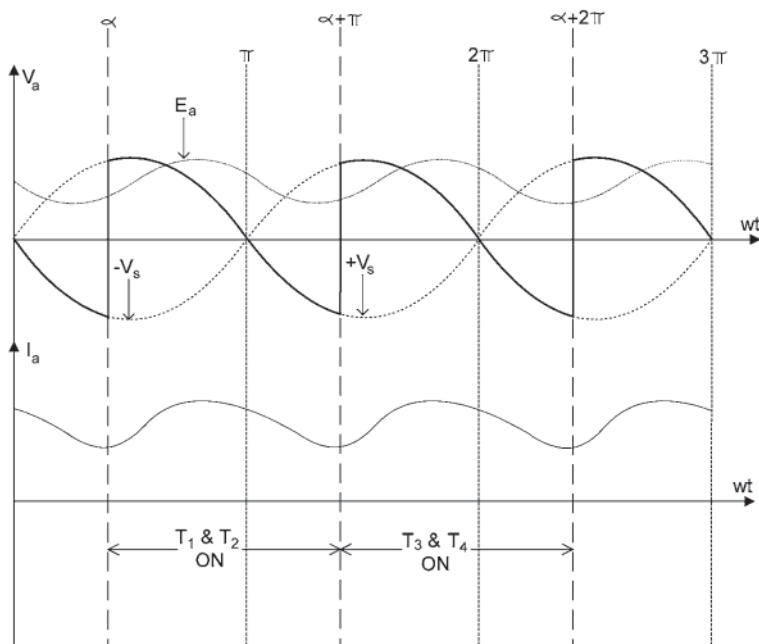


FIGURE 3.9 Waveforms of a single-phase, full-wave controlled rectifier in CCM.

cost, low maintenance, and high efficiency. To control any motor, a strong understanding of the motor equations is needed. Before discussing the phase-controlled induction motor drives, the necessary equations are reviewed.

An induction motor is very similar to a transformer. The induction motor is an AC machine in which alternating current is supplied to the stator directly and to the rotor windings by induction, like a transformer. There are two types of induction motors: a wound-rotor induction motor and a squirrel-cage rotor induction motor. The wound rotor has slip rings mounted on the rotor shaft. These slip rings enable

the user to access the rotor winding. For steady-state operation, these windings are shorted. A squirrel-cage rotor has conducting bars embedded in slots in the rotor magnetic core. These bars are short-circuited at each end.

The synchronous speed depends on the number of pole pairs and the frequency of the source. Synchronous speed (N_s) in revolutions per second is given by

$$N_s = \frac{f}{P}$$

where f is the frequency of the source and P is the number of pole pairs. The difference in rotor speed N and synchronous speed N_s is represented by slip s , which is

$$s = \frac{N_s - N_r}{N_s}$$

At full load, slip is in the range of 2–3%. A very important characteristic of the induction motor is the speed-torque. To develop the torque equation of the induction motor the approximate equivalent circuit of an induction motor is used. [Figure 3.10](#) shows the approximate equivalent circuit of an induction machine.

The power transferred from the stator to the rotor is called the air gap power P_g . The air gap power is the product of the torque T and the synchronous speed ω_s in radians. Using the equivalent circuit, the air gap power can be represented with motor parameters. The air gap power is defined as

$$P_g = T\omega_s$$

$$P_g = \frac{R_2'}{s} I_2'^2$$

Mechanical power P_m is the product of torque and rotor speed ω . Also using the equivalent circuit, the mechanical power can be represented using the motor parameters. P_m is represented by

$$P_m = T\omega$$

$$P_m = R_2' \left(\frac{1}{s} - 1 \right) I_2'^2$$

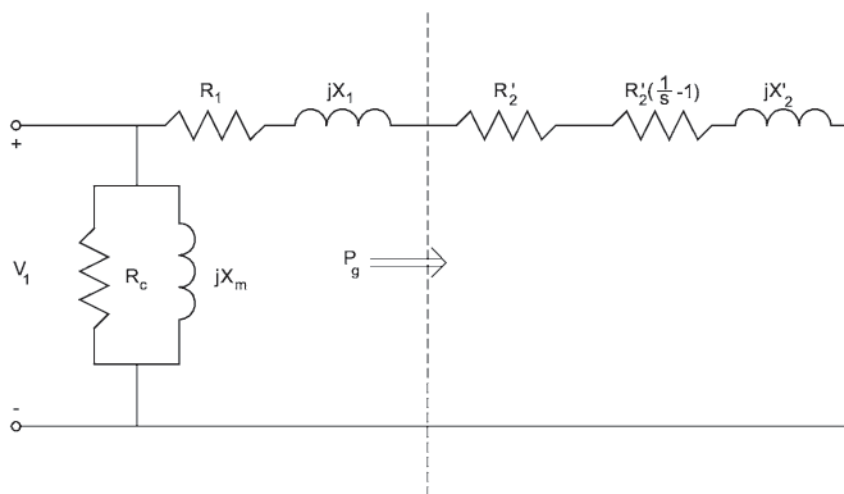


FIGURE 3.10 Approximate equivalent circuit of an induction machine.

Combining these equations, torque can be represented by

$$T = \frac{P_g}{\omega_s} = \frac{(R'_2/s)I_2^2}{\omega_s}$$

and

$$T = \frac{P_m}{\omega} = \frac{R'_2(1/s - 1)I_2'}{\omega}$$

Using the equivalent circuit and the above equations, torque is represented as a function of voltage and speed:

$$T = \frac{R'_2/s}{\omega_s} I_2'^2 = \frac{V_1^2}{\omega_s} \frac{R'_2/s}{(R_1 + R'_2/s)^2 (X_1 + X'_2)^2}$$

This equation represents the torque of an induction motor as a function of voltage and speed. If the voltage is varied, the torque of the motor changes. If the frequency is varied, the speed of the motor changes.

Saturation will occur if the voltage is very large or the frequency is very low. To obtain optimal flux operation, V/f should be kept constant. This will not make the motor go into saturation.

A very simple phase-controlled induction motor is explored. To control a three-phase induction motor, an AC/AC converter can be used. Figure 3.11 shows a three-phase AC/AC converter. Notice that each phase has two thyristors. The firing angles of the thyristors in each phase are 180 degrees apart and are positioned opposite of each other. In addition, as expected, each phase is 120 degrees apart. To simplify the analysis of the phase-controlled induction motor drives, only one phase of the AC/AC converter is examined. Figure 3.12 shows phase A of the converter.

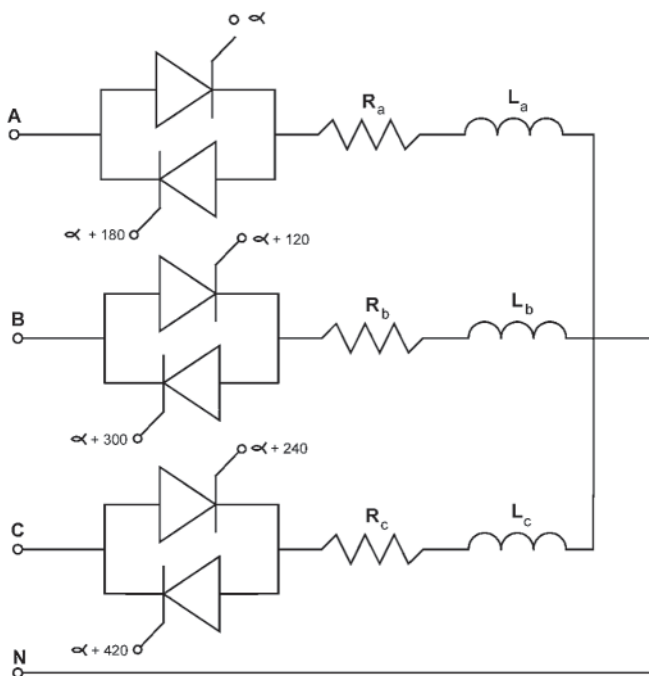


FIGURE 3.11 AC/AC converter.

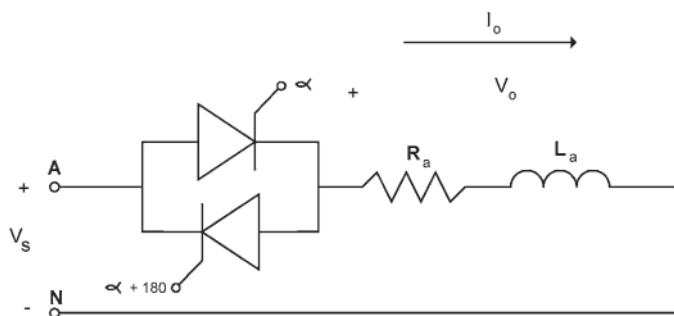


FIGURE 3.12 Phase A of the AC/AC converter.

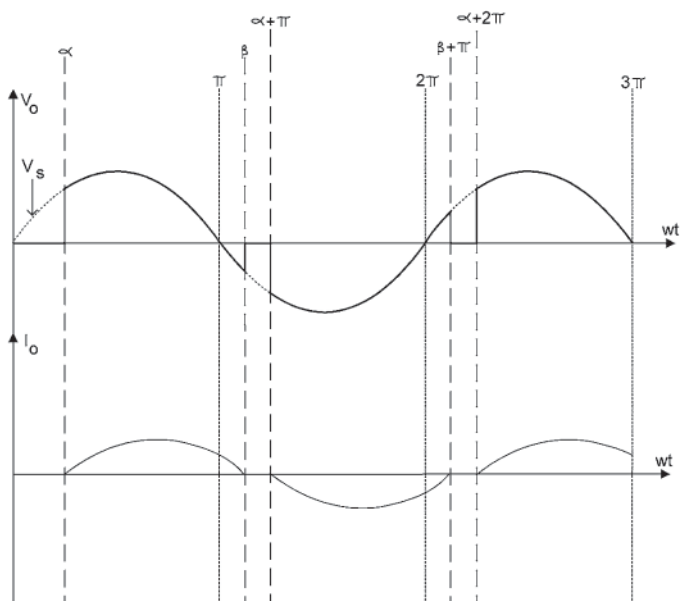


FIGURE 3.13 Waveforms of phase A of the AC/AC converter.

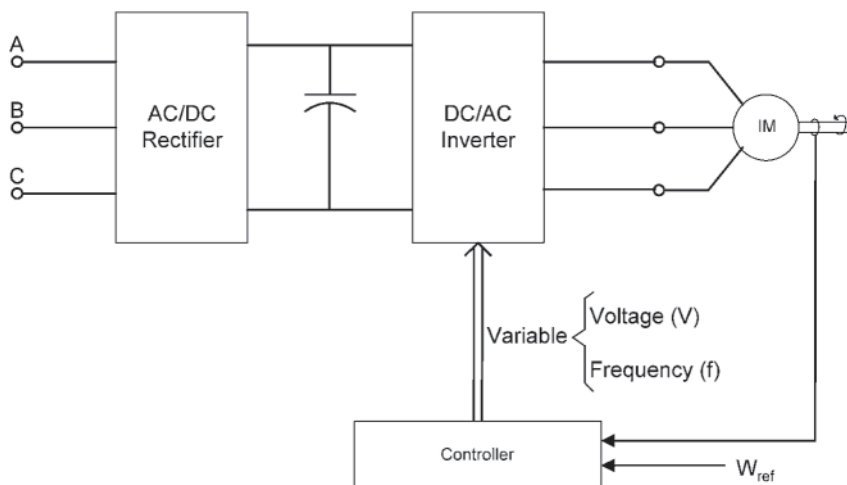


FIGURE 3.14 Block diagram of an advanced induction motor drive.

The waveforms of the circuit of Fig. 3.12 are shown in Fig. 3.13. This is not the most effective way of controlling an induction motor. The quality of the output voltage is not good. Furthermore, as mentioned earlier, to obtain the optimal flux operation V/f should be kept constant. Using an AC/AC converter does not keep V/f constant. A more effective induction motor drive is shown in Fig. 3.14. A constant voltage and frequency three-phase source is the input. With the AC/DC rectifier, DC/AC inverter, and controller, the voltage and frequency can be varied. The control can be used to keep V/f constant and provide optimal flux operation.

3.6 CONTROL OF DC MOTORS USING DC/DC CONVERTERS

Using DC/DC converters to control DC motors is very effective. The speed of the motor is controlled by the on and off time of the DC voltage. This is done through different switching schemes. The switching schemes are varied to produce the control needed.

To understand the switching schemes, one must first understand some definitions. Figure 3.15 shows a typical voltage graph produced by a DC/DC converter. It shows a series of pulses. On the graph, the on time t_{on} and off time t_{off} are defined. From these quantities, the period T and duty cycle d are defined as follows.

$$T = t_{on} + t_{off}$$

$$d = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}$$

Using these definitions, different switching schemes can be defined. There are two main switching schemes. The first is pulse width modulation (PWM). In PWM, the period is constant and the duty cycle is variable. However, the duty cycle is limited between zero and one; therefore, the on time is less than the period. The second switching scheme is frequency modulation (FM). Within FM, there are two basic conditions. One is where t_{on} is constant and the period is varied. Another is when t_{off} is constant and the period is varied. Figure 3.16 shows the different switching schemes. Comparing the two different switching schemes, PWM has fewer harmonics and produces less noise.

Figure 3.17 shows a DC separately excited motor controlled by a DC/DC converter. To simplify the analysis, the switch Q will be assumed to be ideal. Another assumption is that E_a will be considered constant. This is a reasonable assumption because I_f will be

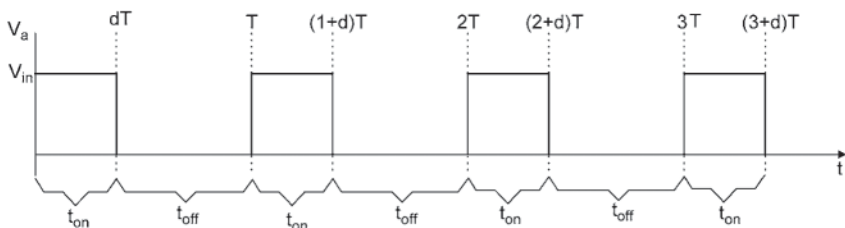


FIGURE 3.15 Typical voltage graph.

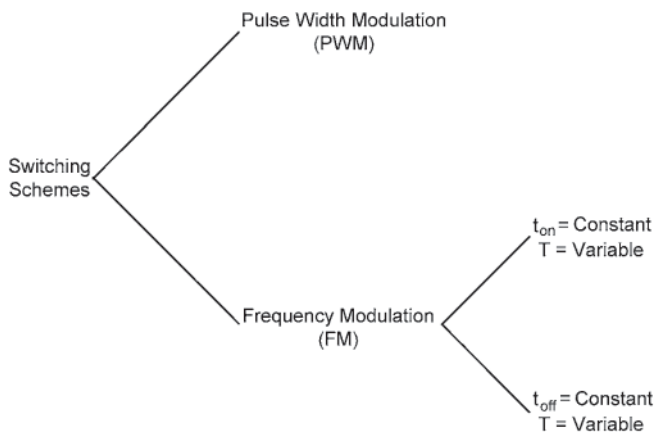


FIGURE 3.16 Switching schemes for DC/DC converter.

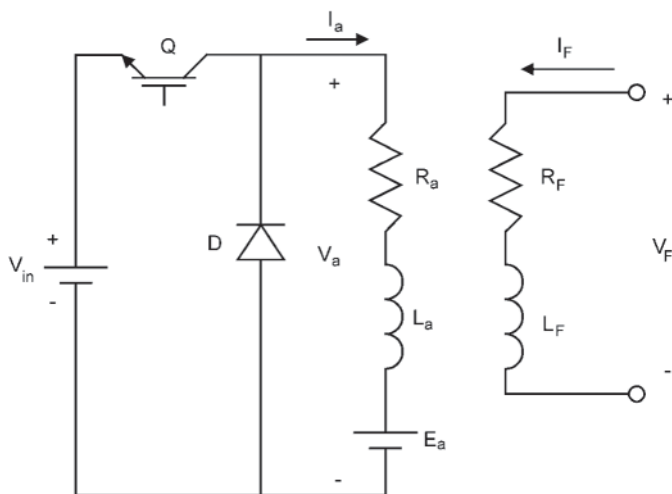


FIGURE 3.17 DC separately excited motor controlled by a DC/DC converter.

constant and we can assume ω is constant. Figure 3.18 shows the output currents produced by the DC/DC converter controlling a DC separately excited motor in continuous conduction mode (CCM).

To find the maximum current, shown in Fig. 3.18, the circuit in Fig. 3.19 will be analyzed. During this time $0 < t < dT$, V_a is equal to $V_{in} - E_a$, and $i_a(t = 0) = I_{a,min}$. Using simple circuit analysis on the circuit in Fig. 3.19, we find that $i_a(t)$ is

$$i_a(t) = \frac{V_{in} - E_a}{R_a} \left(1 - e^{-\frac{R_a t}{L_a}} \right) + I_{a,min} e^{-\frac{R_a t}{L_a}}$$

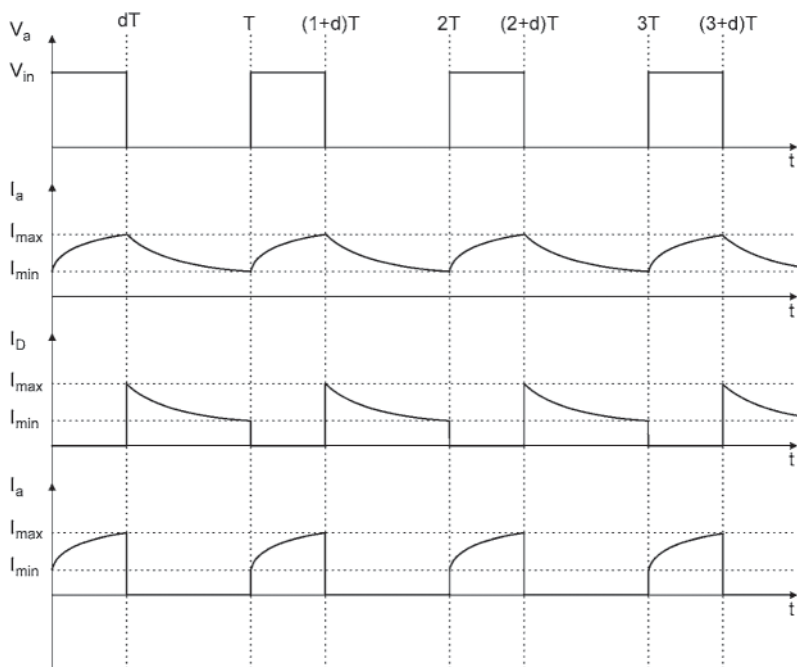


FIGURE 3.18 Current graphs in CCM.

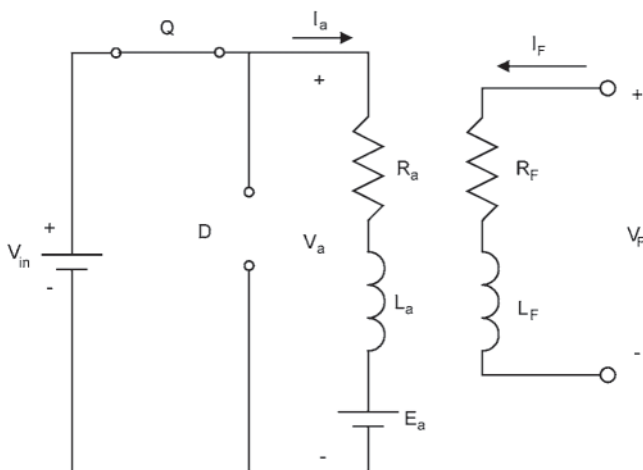


FIGURE 3.19 Continuous conduction mode when $0 < t < dT$.

Now, as seen from Fig. 3.18, $i_a(t = dT) = I_{a,max}$; therefore,

$$I_{a,max} = \frac{V_{in} - E_a}{R_a} \left(1 - e^{-\frac{R_a}{L_a}dT} \right) + I_{a,min} e^{-\frac{R_a}{L_a}dT}$$

Figure 3.20 shows the circuit during $dT < t < T$. During this time interval, Q is off and D is conducting.

Using the fact that V_a is equal to zero and $i_a(t = dT) = I_{a,max}$, we can find the current. From Fig. 3.20, the current is

$$i_a(t) = \frac{-E_a}{R_a} \left(1 - e^{-\frac{R_a}{L_a}(t-dT)} \right) + I_{a,max} e^{-\frac{R_a}{L_a}(t-dT)}$$

Now, as seen from Fig. 3.18, $i_a(t = T) = I_{a,min}$; therefore,

$$I_{a,min} = \frac{-E_a}{R_a} \left(1 - e^{-\frac{R_a}{L_a}(T-d)T} \right) + I_{a,max} e^{-\frac{R_a}{L_a}(T-d)T}$$

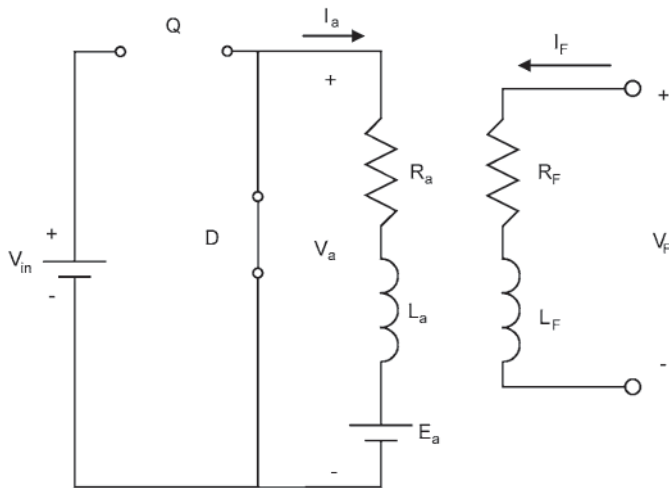


FIGURE 3.20 Continuous conduction mode when $dT < t < T$.

From these equations, the relations for $I_{a,min}$ and $I_{a,max}$ are found as follows:

$$I_{a,min} = \frac{V_{in} e^{\frac{R_a}{L_a} dT} - 1}{R_a e^{\frac{R_a}{L_a} T} - 1} - \frac{E_a}{R_a}$$

$$I_{a,max} = \frac{V_{in} 1 - e^{-\frac{R_a}{L_a} dT}}{R_a 1 - e^{-\frac{R_a}{L_a} T}} - \frac{E_a}{R_a}$$

In order to find the relationship between the duty cycle and voltage, the average V_a must be found:

$$\langle V_a \rangle = \frac{1}{T} \int_0^T V_a dt = \frac{1}{T} \int_0^{dT} V_{in} dt = d V_{in}$$

The speed of the DC separately excited motor can be changed by changing the duty cycle. If the inductance of the motor is too small, the current will go into discontinuous conduction mode. [Figure 3.21](#) shows the voltage and current waveforms for DCM.

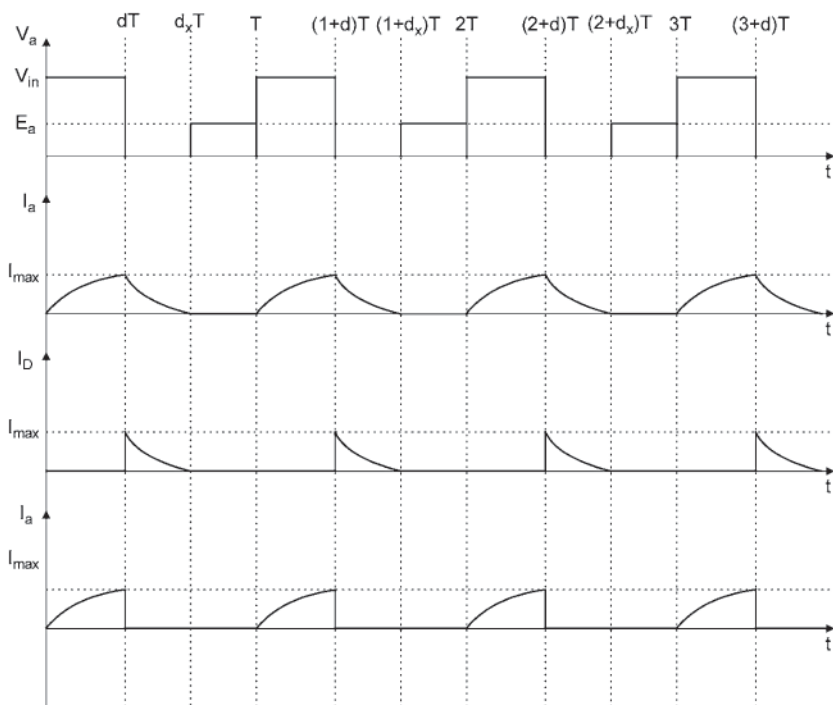


FIGURE 3.21 DC separately excited motor in DCM.

To perform the analysis for DCM, different modes of the circuit will be analyzed. Figure 3.22 shows the circuit for $0 < t < dT$. During $0 < t < dT$, V_a is equal to $V_{in} - E_a$ and $i_a(t=0) = 0$. Therefore,

$$i_a(t) = \frac{V_{in} - E_a}{R_a} \left(1 - e^{-\frac{R_a t}{L_a}} \right)$$

In DCM, $I_{a,min}$ is equal to zero and $I_{a,max}$ is simply equal to

$$I_{a,max} = \frac{V_{in} - E_a}{R_a} \left(1 - e^{-\frac{R_a dT}{L_a}} \right)$$

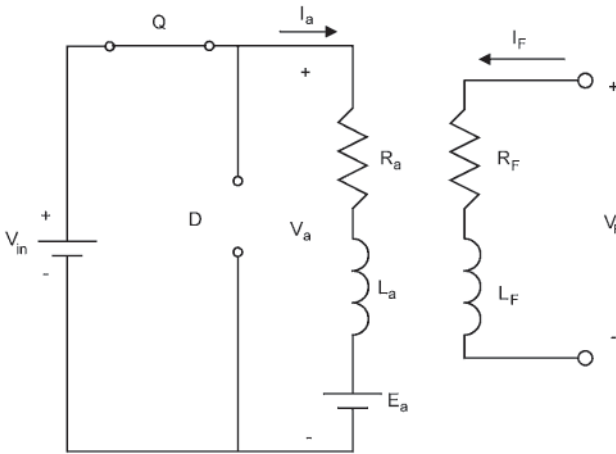


FIGURE 3.22 Discontinuous conduction mode during $0 < t < dT$.

From Fig. 3.21, we see that during the time $dT < t < d_x T$, the current is decreasing until it reaches zero. Figure 3.23 shows the circuit during this time interval.

The equation for $i_a(t)$ for the time shown in Fig. 3.23 is

$$i_a(t) = \frac{-E_a}{R_a} \left(1 - e^{\frac{R_a}{L_a}(t-dT)} \right) + I_{a,\max} e^{\frac{R_a}{L_a}(t-dT)}$$

To find the value of d_x , the above equation can be solved for the condition $i_a(t = d_x T) = 0$. The final portion of the graph shown in Fig. 3.21 to analyze is $d_x T < t < T$. Figure 3.24 shows the circuit during $d_x T < t < T$. During this time interval, Q and D are not conducting. This makes $i_a = 0$ and $V_a = E_a$.

In conclusion, electric motor drives have advanced since the old mechanically linked systems. The new drives are more accurate and consume less power. For example, slowing a pump or fan by using an electric drive reduces energy consumption more effectively than allowing the motor to run at constant speed and then restricting or bypassing the flow with a valve or damper.

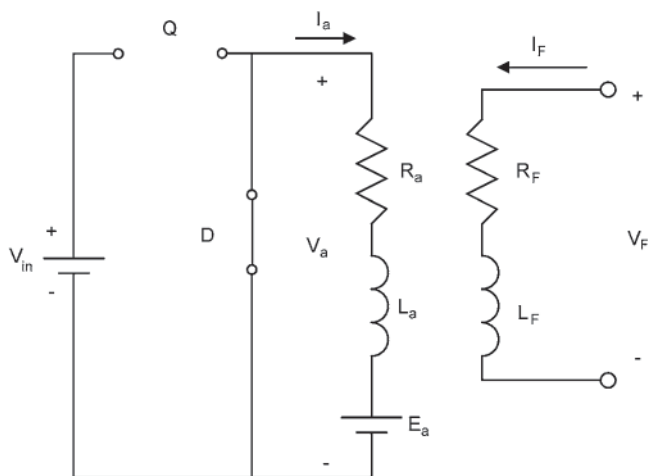


FIGURE 3.23 Discontinuous conduction mode when $dT < t < d_x T$.

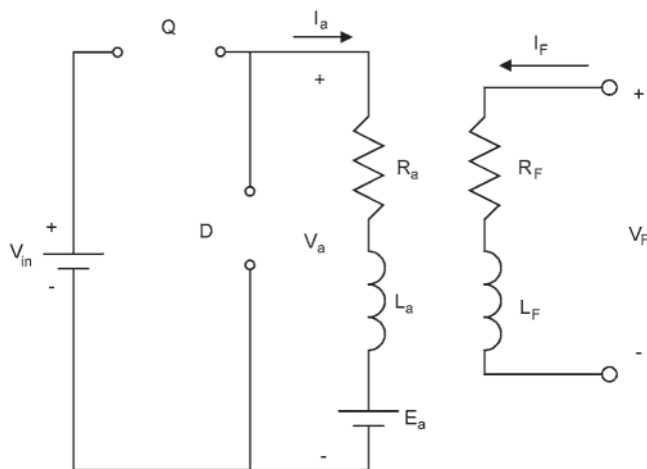


FIGURE 3.24 Discontinuous conduction mode when $d_x T < t < T$.

In addition, electric motor drives can provide benefits when starting a motor. They can be used to slowly start the motor. The slow start reduces the mechanical stress on the motor and the load equipment. By slowly starting a motor, the voltage sag is reduced. Voltage sag causes lights to dim and other equipment like computers to shut down.

The future of electric motor drives is to have a simple motor and a complex power electronic converter. The power electronic converter is software based, while the electric machine is hardware based. Software is easier to manipulate than hardware. Furthermore, from a manufacturing standpoint, it is less expensive to have a software intensive drive compared to a hardware intensive drive. With the majority of electric power consumed by electric motors, the future of electric motor drives is good.

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